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ORIGINAL ARTICLE

Hydrological foretelling uncertainty evaluation of water balance components and sediments yield using a multi-variable optimization approach in an external Rif's catchment. Morocco



Abdessalam Ouallali^{a,*}, Hamza Briak^b, Habiba Aassoumi^a, Mohamed Beroho^c,
Naima Bouhsane^d, Mohamed Moukhchane^e

^a Environmental Geology and Natural Resources Laboratory, Cartography and Digital Technologies Team, Abdelmalek Essaadi University, Faculty of Sciences, Mhannech II, B.P. 2121, 93002 Tetouan, Morocco

^b Center of Excellence for Soil and Fertilizer Research in Africa (CESFRA), Mohammed VI Polytechnic University, (UM6P), Morocco

^c Department of Earth Sciences, Faculty of Sciences and Techniques (FST), Abdelmalek Essaadi University, Tangier, Morocco

^d Laboratory of Radiochemistry and Nuclear Chemistry, Department of Chemistry, Mohammed V University, Faculty of Sciences, Rabat, Morocco

^e Departement of Earth and Lif Siences. Abdelmalek Essaadi University, Ecole Normale Supérieure, Tetouan, Morocco

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Abstract Sedimentary and aquatic dynamics are currently causing major environmental problems in the Mediterranean countries, water and soil resources are steadily decreasing over time. Therefore, simulation and estimation of flows and sediments have currently a direct implication in the sustainable management of water and soils. In the present study, a Mediterranean watershed (North-West of Morocco) was benefited from the functionalities of Hydrological Model SWAT, version 2012 (semi-distributed and physically based), by adopting a monthly simulation. The main objective of this study is to calibrate and validate the SWAT model in the Arbaa Ayacha watershed (18,854 ha) between 1980 and 2000 by a multi-objective optimization approach using the Sufi-2 algorithm of the SWAT-CUP program. The performance of the model was tested using three objective functions NSE, PBIAS and R2, while the sensitivity analysis of the model was performed by adjusting 19 parameters of sensitivities related to flow rates and sediment concentrations. The results obtained are satisfactory with a significant correlation between the observed and simulated values of variables flow and sediments. The results also show that evapotranspiration and surface runoff are predominante in the basin compared to the other components of the water balance, while the sediment yield was estimated at 28.09 t/ha/year. Since the model is validated in the study area, it

* Corresponding author.

E-mail addresses: abdessalam.ouallali@gmail.com (A. Ouallali), hamza.briak@um6p.ma (H. Briak).

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will later be used to simulate the evolution of scenarios based on climate change and land use. It will also help to determine the best management practices in the watershed.

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1. Introduction

In recent years, water erosion is ranked among the most threatening environmental phenomena for human life [1]. This phenomenon includes the detachment, transport and deposit of materials, causes a serious socio-economic and environmental problems [2]. Soils affected by erosion are progressively depleted in mineral and organic nutrients [3], which causes a decrease in agricultural production. Water resources are also progressively less important by the clogging of dams reservoirs following the sediment load that moves from upstream to downstream slopes. The main causes of erosion and soils degradation are storms, overgrazing, friable lithology, destruction of vegetation cover, steep slopes and bad agricultural practices [4]. Morocco is not immune to the repercussions caused by water erosion, several studies have shown that this phenomenon is becoming more intense over time by threatening the economy of the country, especially that agriculture is a predominant sector that generates about 14% of gross domestic product [5]. Moroccan Soils are progressively degraded due to intense land use degradation and overgrazing, to this is added the clearing of vegetation to produce more agricultural land or urban areas [6]. The Moroccan Rif, given its topographic, lithological, biological and climatic characteristics, is much more vulnerable to water erosion [7]. For this reason, several erosion studies have been carried out in the Rif to better guide anti-erosion interventions in order to preserve water resources and soil fertility as long as possible. The SWAT model (Soil and Water Assessment Tools) is one of recent techniques mostly used in soil erosion studies and in the evaluation of hydrological balance in watersheds [8,9]. It is a semi-distributed and physically based model [10] first developed by USDA-ARS (United States Department of Agriculture-Agricultural Research Service) [11]. At the International scale, SWAT was able to simulate river flows in more than 6000 stations in the United State [10]. In Africa this model was exploited to establish a large-scale hydrological balance and to assess global climate change for the entire continent [12,13]. The SWAT model has also demonstrated its accuracy and reliability in the evaluation of flash floods [14] and in the complexity solving of the hydrological cycles especially when the studied area is affected by many surface depressions (lakes and potholes) [15]. However, the application of the hydrological model SWAT in Morocco remains very limited. It is not very widespread, despite being considered by the United States Environmental Protection Agency (EPA) as the best scientific tool for integrating punctual and unpunctual data sources [16], including the purpose of planning and managing with sovereignty the exploitation of water and soil resources [17,18]. SWAT requires during its running, a step of calibration, validation and sensitivity analysis and uncertainties by comparing the values of the flows simulated to flows measured in the gauging stations [19]. The calibration has been considered an essential stage for the acceptance of SWAT simulation

results [20,21]. However, there is no universal and common calibration procedure in the scientific bibliography [22]. Some researchers use the method of Hydrograph separation methods [23], others prefer optimization algorithms and multi-objective approaches [24] while some others refer to sequential or simultaneous methods [25]. In the present study, the Arbaa Ayacha watershed was chosen to serve the SWAT model by a multi-variable optimization approach. This basin undergoes a double Mediterranean and Atlantic climate influence and presents climatic, topographic, lithological and biological characteristics favoring water erosion. This area must be developed to preserve soils and water resources, especially since a dam is projected downstream of this basin in the coming years (2030) (ABHL, 2012, PDAIRE. Tech. note). The main objectives of this study are: (i) Establish a hydrological model for the Arbaa Ayacha watershed using the SWAT model features, (ii) Evaluate the performance of the model in the basin, its calibration and validation using a multi-variable and simultaneous approach (Flow and sediments concentration), (iii) Identify the sensitivity parameters most sensitive to sediments and flows for the study area, (iiii) Estimate soil loss and sediment yield downstream of the basin and identify areas most vulnerable to erosion, (iiiii) predict water balance components and water yield in this basin and identify the most dominant water balance parameters in the region.

2. Materials and methods

2.1. Study area

The Arbaa Ayacha catchment with an area of 18,854 ha is located in the northwestern part of the western Rif midway along the national road connecting the Tetouan and Larache towns (Fig. 1). This area is characterized by a sub-humid climate with an Atlantic and Mediterranean influence. The average annual rainfall is 726.7 mm, measured at the Arbaa Ayacha meteorological station, while the average annual temperature equal to 17.85 °C [26]. The Digital Terrain Model of this area shows altitudes ranging from 6 m at the outlet to 549 m at the highest point in the basin. The slopes vary from 0 to 85.22% with a slope index equal to 0.016 m/km testifying to the hilly character of the area. The calculated Gravelius Kg index gave a value of 1.4 and indicates an elongated pelvis shape, 4.6 times longer than the width [7]. The lithological formations outcropping in the watershed are mostly friable in the form of whitish marls with limestone flint [27], sands of Villafranchien and Cretaceous clay formations [28], the only resistant rock formations appear upstream of the basin in the form of the sandstones of the numidian nappe [29]. The land cover map of this area shows that most of the basin is occupied by cultivated land followed by degraded matorrals and bare land, while the dense vegetation is very restricted in the form of some old white pine reforestation [30].

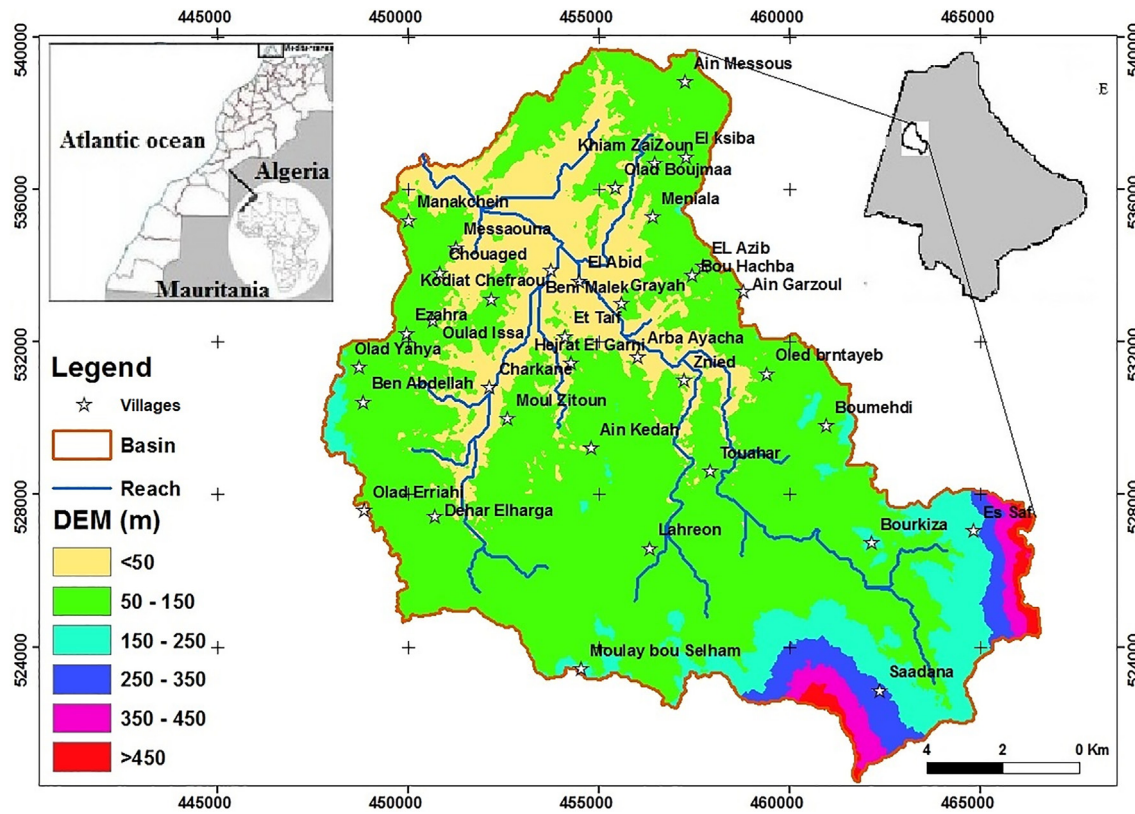


Fig. 1 Geographical location of the study area and Digital Terrain Model.

2.2. Implementation of the model SWAT and data input

The SWAT model operates at several scales ranging from sub-daily, daily, monthly up to annual scale. ArcSWAT-2012 used in this study is a component added to the ArcGIS 10.3 software to facilitate the execution of the hydrological model. This interface uses data input related to soil, land cover management, topography and climate. Missing data of climate related to humidity, solar, and wind speed can be simulated by SWAT. It takes into consideration infiltration, surface runoff, percolation, evaporation, evapotranspiration, and lateral and underground flows for assessment of hydrological processes. Further details on the method of implementation of the SWAT model step by step are detailed in the SWAT manual [31] and in the study of Abbaspour et al. [16–32]. In general, SWAT can simulate the hydrological cycle and water balance in the watershed using the following equation [33]:

$$SWt = SW0 + \sum_{n=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

With: SWt is the soil water content in mm, $SW0$ is the water available to plants in mm, R_{day} is the precipitation in mm, W_{seep} is the percolation in mm, Q_{gw} is low flow in mm and t time in days.

The SWAT model also assesses the quantities of sediment discharged at the outlet of the basin and estimates the sediment yield based on the factors of the Modified Soil Loss Equation (MUSLE) [34–35]:

$$Sed = 11.8(Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{usle} \cdot C_{usle} \cdot P_{usle} \cdot LS_{usle} \cdot F_{CRFG} \quad (2)$$

With: Sed is the sediment yield in tons, Q_{surf} is the volume of surface runoff (mm-H₂O/ha), q_{peak} is the maximum flow of runoff (m³/s), $area_{hru}$ is the area of HRUs in ha, K_{USLE} is the soil erodibility factor (0,013 tonne m²h/(m³-tonne métrique cm)), C_{USLE} is the factor in relation to vegetation cover, P_{USLE} is the factor of the anti-erosion practices, LS_{USLE} is the topographic factor and F_{CRFG} is the factor of coarse fragments.

In this study, land cover data are retrieved from the land use map of the Arbaa Ayacha watershed. This map was developed using remote sensing data and GIS. A Landsat 8 image dated 2015 has undergone several radiometric, geometric and atmospheric treatments, then it has been classified under the ENVI software to highlight the different classes of land use with several units have been verified in the ground (Fig. 2). Thereafter the land cover map has been re-classified according to SWAT guidelines codes. The pedological data of the watershed are extracted from the soil map of the Tangier-Tetouan area (edition 1/50000), the class of vertisols and poorly developed soils occupy a large proportion in the watershed and are mainly located in the center and downstream of the basin (Fig. 3). This map has been declassified in 8 classes, then renamed according to the SWAT model guidelines. The physicochemical parameters necessary for the execution of the model have been measured, we cite as examples the texture, the number of horizons of the soils, the percentage of clay, silts and sand. The topographic data were extracted from the Digital Terrain Model (ASTER-GDM with a resolution of

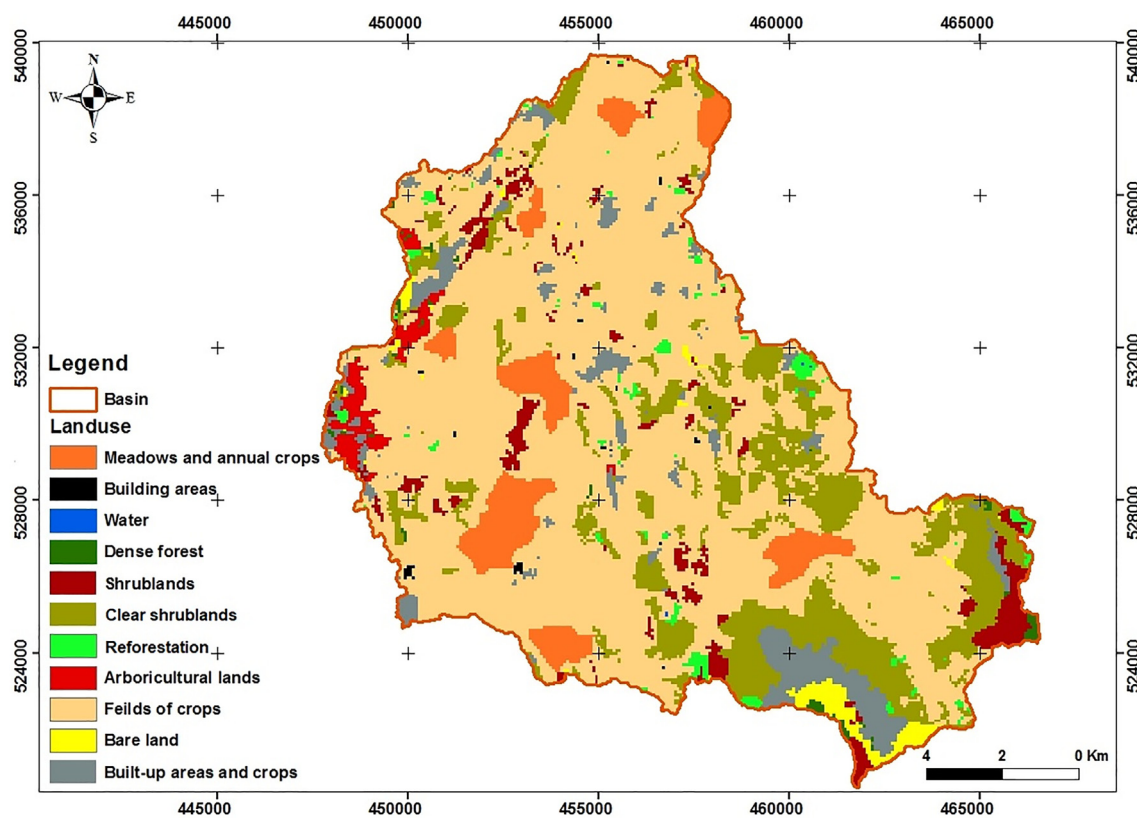


Fig. 2 Land use map.

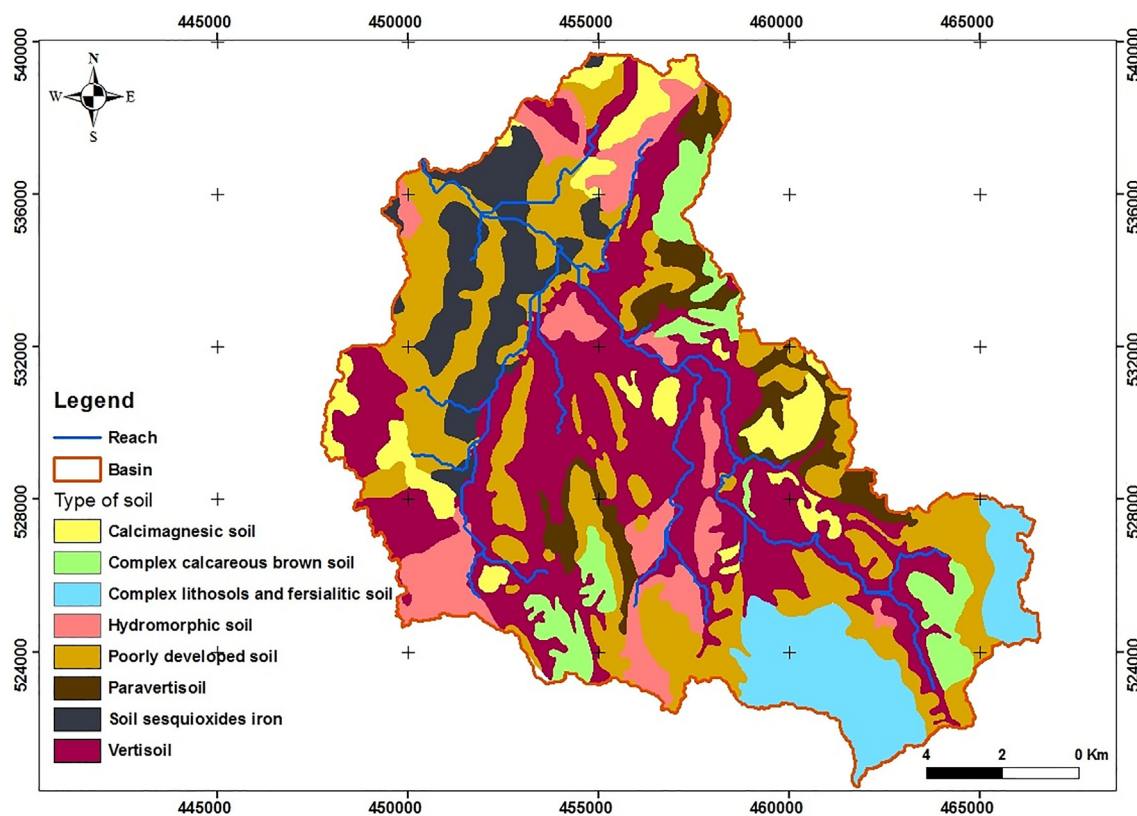


Fig. 3 Map of soil types in the study area.

25 m) (Fig. 1). ArcSWAT-2012 uses this DTM for the generation of flow direction, flow accumulations and slope, these parameters are used in addition to the location of the outlet, to delineate automatically the sub-watersheds (Fig. 4). SWAT introduces soil map (Fig. 3), slope map (Fig. 5) and land cover data to extract the homogeneous hydrologic units (HRUs) that characterize the basin.

The observed climate data were retrieved from the Loukkos Watershed Agency (ABHL) as daily rainfall values and maximum and minimum temperatures. The values of relative humidity, solar and wind speed are simulated using the components of ArcSWAT-2012. While daily values of flows and sediment concentrations were measured in the hydrometric station installed in the watershed.

By running SWAT, ArcSWAT-2012 creates tabular data for sub-basins, HRUs and rivers. It estimates from the input data the values of each parameter of the hydrological cycle as a function of time. It allows to restore the simulated data of sediments yield, water yield, evaporation, evapotranspiration, surface, sub-surface and underground flows, percolation, simulated flows and simulated sediments. These data must be calibrated and validated to reflect the realities of the grounds, for this reason, SWAT-CUP (SWAT Calibration and Uncertainty Procedures) was chosen as software allowing both the calibration and the validation of the results simulated by the ArcSWAT-2012.

2.3. SWAT-CUP

The SWAT-CUP model is a program mainly intended for calibration, validation and sensitivity analysis of data simulated

by the SWAT model [36]. It is a program that uses SWAT output files (TxtIn/Out) developed to give more reliability to the results according to several parameters influencing the hydrological cycle such as CN2, Sol_AWC, SOL_K etc. The Sufi-2 algorithm was used in this study since it allows the calibration, validation and analysis of the sensitivity and uncertainty of simulated flows and sediments compared to those observed [37]. The Sufi-2 algorithm releases and predicts values of measured variables (flow and sediment) in an uncertainty framed by 95PPU of the SWAT-CUP program [16], this prediction is made according to the sensitivity parameters used for the calibration of the model, and each parameter is framed by a minimum and maximum value [14]. Abbaspour et al. [16] have proposed two factors to evaluate the reliability of the model uncertainty calibration, the first factor named P expresses the fraction of measured data (with their errors) framed by the 0–1 interval of 95PPU, so the quantity 1-P corresponds to the errors of the model [38]. The second factor named R is the ratio of the standard deviation of the measured variable to the width of the 95PPU band [16]. This factor, which must always be less than 1.5, also makes it possible to test the reliability of the calibration and validation of the model. Sufi-2 can use eleven objective functions in the file observed.txt, and the choice of the type of the objective function greatly influences the possible solutions for the calibration [22], the choice to be made depends mainly on the goals laid out for the study. In our case, Nash-Sutcliffe model efficiency coefficient (NSE) (Eq. (3)), Percentage Bias (PBIAS) (Eq. (4)) and the coefficient of determination (R²) (Eq. (5)) were used to assess the assimilation performance of the output data.

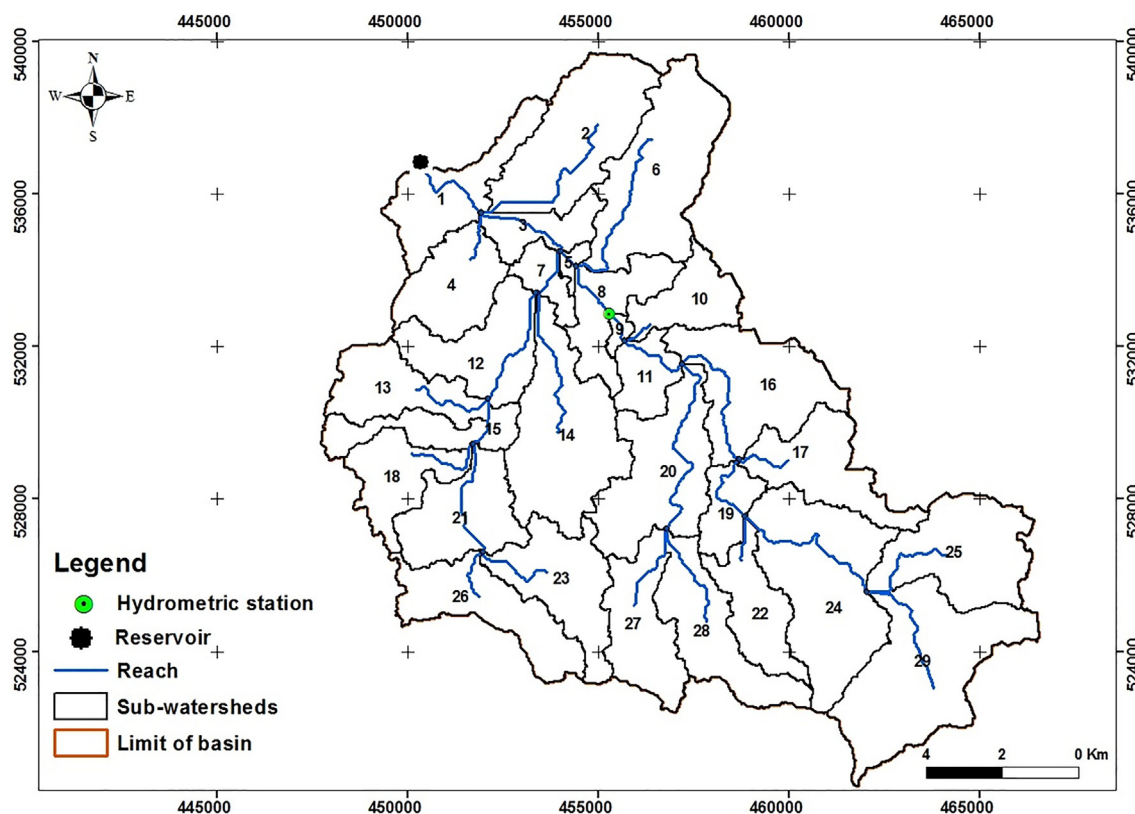


Fig. 4 Map of sub-watersheds.

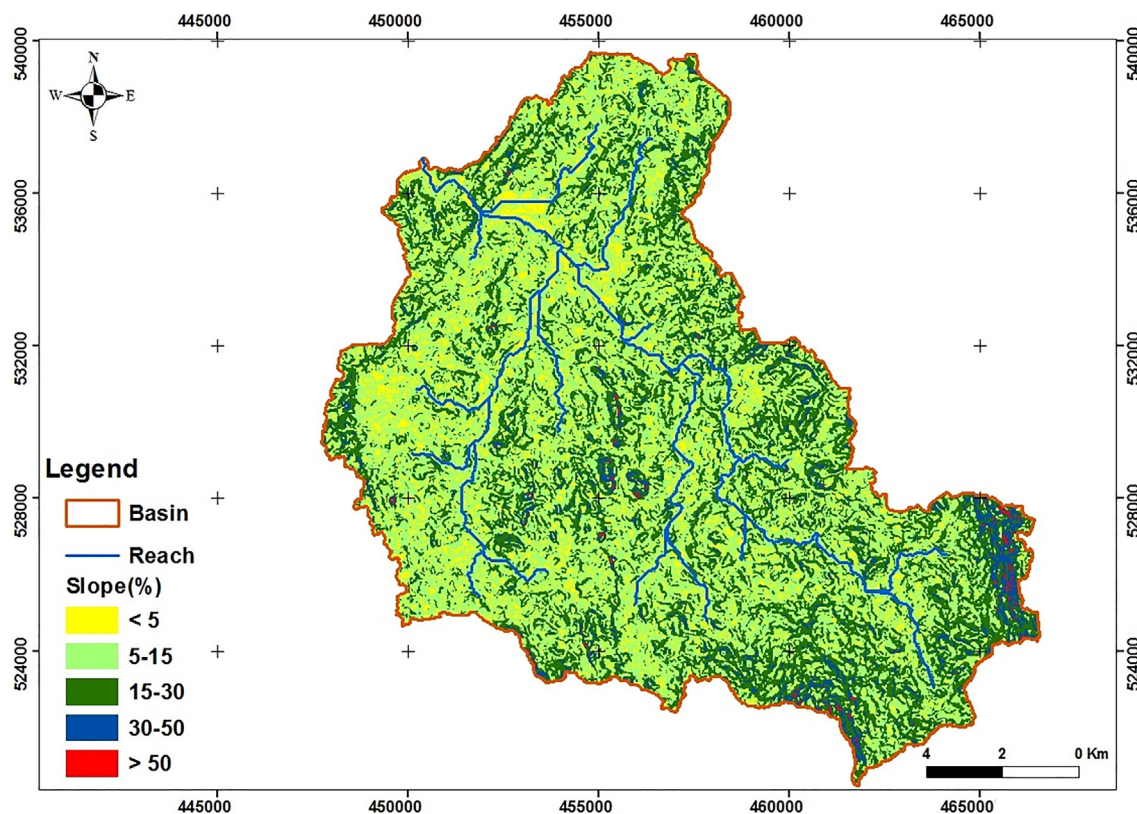


Fig. 5 Map of slope classes in the study area.

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2} \quad (3)$$

$$PBIAS = \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim}) * 100}{\sum_{i=1}^n Y_i^{obs}} \quad (4)$$

where Y^{obs} refers to the stream flow ($m^3 \cdot s^{-1}$) observed at time t , Y^{sim} is the stream flow ($m^3 \cdot s^{-1}$) estimated at time t .

$$R^2 = \frac{(\sum_{i=1}^n (Q_{s_i} - Q_s)(Q_{m_i} - Q_m))^2}{\sum_{i=1}^n (Q_{s_i} - Q_s)^2 \sum_{i=1}^n (Q_{m_i} - Q_m)^2} \quad (5)$$

where R^2 is the coefficient of determination, Q_{m_i} is the value observed, Q_{s_i} is the simulated value, Q_m is the average of the observed values and Q_s is the average of the simulated values.

2.4. Parameters and sensitivity analysis of the model

In this study, available observed monthly data for both variables (flow and sediment) range from 1980 to 2000. This period was chosen based on the availability of the observed data and their reliability. This period was divided into three parts for the purposes of the model execution. Five years were left for warm-up period, eight years (1985–1992) for the calibration period and eight years for the validation period (1993–2000). The sensitivity analysis is based on the determination of the parameters that control the simulated variables. These parameters have been subdivided into two groups, one corresponding to the parameters influencing flows and the other correspond-

ing to the parameters influencing sediments (Table 1). The ranges of variation of each parameter as well as their identification code (a, v, r) are taken from the SWAT-CUP manual and the studies of Abbaspour [39] and Arnold et al. [40]. The Sufi-2 algorithm uses these parameters to determine the most significant optimal ranks for the model. After each iteration, SWAT-CUP proposes new intervals to be considered in the next iteration for each parameter. A total of 1500 iterations were completed as recommended by Yang et al. [41], however, after iteration number 400, the values of NSE and PBIAS remain unchanged. These two objective functions, when they exceed 0.5 for NSE, and less than 25% for PBIAS, the simulation results will be considered acceptable and satisfactory [42,43].

3. Results

3.1. Model sensitivity analysis

ArcSWAT has subdivided the watershed into 29 sub-basins and 167 HRUs with sub-basin number 9 contain the hydro-metric station that measures flow and sediment concentration (Fig. 4). Tables 2 and 3 represent the optimal values of the 19 parameters used for calibration and validation of flows and sediments over a 21-year period. A high response of an output parameter indicates a high sensitivity of this parameter to the output results [44]. Considering that a parameter is sensitive when its value of P-stat is less than 0.5 or close to 0, twelve parameters are considered the most sensitive for our zone. They are: CN2.mgt, GW_DELAY.gw, ALPHA_BF.gw,

Table 1 Initial ranges of sensitivity parameters used for model calibration and validation (V: means the existing parameter value is to be replaced by a given value; R: means an existing parameter value is multiplied by $(1 + \text{a given value})$).

Parameter	Definition	Initial Range	Variable
R_CN2.mgt	runoff curve number	−0.2 to 0.2	Flow
R_SOL_AWC(..).sol	Available water capacity of the soil layer	−0.25 to 0.25	Flow
R_SOL_BD(..).sol	Moist bulk density	−0.5 to 0.6	Flow
R_SOL_K(..).sol	Saturated hydraulic conductivity	−0.25 to 0.25	Flow
V_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0–5000	Flow
V_REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” to occur (mm)	0–500	Flow
V_ESCO.hru	Soil evaporation compensation factor	0.01–1	Flow
V_SURLAG.bsn	Surface runoff lag time	0.5–10	Flow
V_GW_DELAY.gw	Groundwater delay (days)	0–500	Flow
V_ALPHA_BF.gw	Baseflow alpha factor (days)	0–1	Flow
V_CH_N2.rte	Manning’s “n” value for the main channel	0–0.3	Flow
V_ADJ_PKR.bsn	Peak rate adjustment factor for sediment routing in the subbasin (tributary channels)	0.5–2	Sediment
V_CH_COV1.rte	Channel erodibility factor	−0.05 to 0.6	Sediment
R_USLE_K(..).sol	USLE equation soil erodibility (K) factor	0–0.65	Sediment
V_SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	0.0001–0.01	Sediment
V_SPEXP.bsn	Exponent parameter for calculating sediment reentrained in channel sediment routing	1–1.5	Sediment
V_USLE_P.mgt	USLE equation support practices	0–1	Sediment
V_PRF_BSN.bsn	Peak rate adjustment factor for sediment routing in the main channel	0–2	Sediment
V_CH_COV2.rte	Channel cover factor	−0.001 to 1	Sediment

GWQMN.gw, CH_N2.rte, SOL_BD(..).sol, REVAPMN.gw for stream flows and USLE_P.mgt, CH_COV1.rte, SPCON.bsn, USLE_K(..).sol, CH_COV2.rte for sediment concentrations. When CN2 increases, runoff increases and infiltration decreases [45], in our study area, this parameter proved to be the most sensitive variable among all flow and runoff sensitivity parameters. CN2 increased from initial value indicating that the Arbaa Ayacha watershed is subject to more intense runoff compared to infiltration. This is mainly due to the marly nature of most lithologic formations in the watershed. Water changes in soil horizons are controlled by the ESCO parameter [46], this parameter has been adjusted to 0.84 to meet the demand for water by evaporation. The value of ALPHA has been adjusted to 0.07, this low value does not lead to an important base flow, since the watershed Arbaa Ayacha is seat of a large runoff during rainy periods. The GWQMN parameter also influences runoff as it controls the amount of water flowing down the ground. The wet bulk density parameter SOL_BD, the groundwater delay GW_DELAY, the minimum water depth in the shallow aquifer so that there is a water movement to the ground (“revap”) or the deep aquifer REVAPMN and the Manning Coefficient “n” of the main channel CH_N2 [11] are also considered sensitive for our study area. Regarding sediment sensitivity parameters, USLE_P is the most sensitive parameter, it has been adjusted to 0.53 and influences soil control practices or tillage activities especially that no land management practice has been carried out in the basin. SPCON and SPEXP parameters control sediment transport in channels and streams [47], in the Arbaa Ayacha watershed, SPCON is much more sensitive compared to SPEXP, its value has been adjusted to 0.02

reducing sediment deposition in streams and amplifying the transport capacity of materials in the channels. CH_COV1 and CH_COV2 are two other parameters affecting the degree of erodibility and the transport capacity of materials in the channels, they were adjusted to 0.46 and 0.42 respectively. These two values close to the maximum value of initial range testify to a significant erodibility of the grounds in the channels especially that the watershed is crossed by several deep ravines sometimes exceeding 4 m of depth. The soil erodibility in the study area is also sensitive to the USLE_K parameter which occupies the fourth class in terms of sensitivity with a value adjusted to 0.32.

3.2. Calibration, validation and analysis of the model performance

The multi-objective and multi-variable calibration strategy is considered by several authors to be more advantageous compared to the uni-objective strategy [48]. This study considers three objective functions for model performance which calculate the efficiency of the model by associating the variance of the measured data with the adjustment quality of the model [49]. Table 4 illustrates the best performances obtained during calibration and validation periods by multi-objective optimization. The NSE, PBIAS and R2 values obtained are acceptable and show a satisfactory simulation and acceptable linearity between the observed and simulated data, especially that R2 is high for both periods. They are increased by passing from the calibration period to the validation period for flow rates, whereas these values are slightly decreased for the sediments concentration between the two periods.

Table 2 Sensitivity parameters used for flow simulation and their calibrated values (V: means the existing parameter value is to be replaced by a given value; R: means an existing parameter value is multiplied by $(1 + \text{a given value})$).

Parameter Names	Rank	Fitted_Value	Min_value	Max_value	P_value
R_CN2.mgt	1	0.027	0.021	0.056	0.000
R_SOL_AWC(..).sol	2	-0.207	-0.207	-0.179	0.743
R_SOL_BD(..).sol	3	0.274	0.245	0.295	0.444
R_SOL_K(..).sol	4	-0.094	-0.094	-0.078	0.909
V_GWQMN.gw	5	578.381	467.975	581.649	0.150
V_REVAPMN.gw	6	142.158	115.311	146.943	0.467
V_ESCO.hru	7	0.841	0.825	0.854	0.787
V_SURLAG.bsn	8	2.482	2.465	2.634	0.959
V_GW_DELAY.gw	9	15.535	11.230	17.667	0.000
V_ALPHA_BF.gw	10	0.071	0.067	0.094	0.000
V_CH_N2.rte	11	0.228	0.227	0.253	0.265

Table 3 Sensitivity parameters used for sediment simulation and their calibrated values (V: means the existing parameter value is to be replaced by a given value; R: means an existing parameter value is multiplied by $(1 + \text{a given value})$).

Parameter Names	Rank	Fitted_Value	Min_value	Max_value	P_value
V_ADJ_PKR.bsn	12	1.872	1.311	2.000	0.682
V_CH_COV1.rte	13	0.461	0.394	0.531	0.004
R_USLE_K(..).sol	14	0.318	0.239	0.415	0.064
V_SPCON.bsn	15	0.002	0.0001	0.003	0.056
V_SPEXP.bsn	16	1.311	1.294	1.405	0.661
V_USLE_P.mgt	17	0.528	0.377	0.558	0.000
V_PRF_BSN.bsn	18	0.594	0.431	0.822	0.712
V_CH_COV2.rte	19	0.420	0.343	0.647	0.305

Table 4 Results of the multi-objective optimization for the calibration and validation period (NSE is the coefficient of Nash-Sutcliffe, R2 is the coefficient of determination and PBIAS is the percentage of Bias).

	Multi-objective optimization			
	Calibration period		Validation period	
	Flows	Sediments	Flows	Sediments
NSE	0.69	0.71	0.81	0.66
PBIAS	-0.7	11.1	-1.3	9.2
R2	0.7	0.7	0.8	0.7

In the first runs of the SWAT model, hydrological cycle factors in the watershed have been underestimated, but after calibration with the model sensitivity parameters, the cycle begins to have logical and acceptable values. The calibration aims to bring the model response as close as possible to the data observed and measured in the hydrometric station. Figs. 6 and 7 show the multi-objective calibration results of flow and sediment variables using SWAT-CUP's Sufi-2 algorithm. These Figures show that the calibration was carried out with great success, since the variation in flow rates and sediments observed and simulated do not show large differences, especially since the correlation coefficient is relatively high (Figs. 8

and 9). According to Uniyal et al [50] and Wang et al. [51], model performance can be tested using sensitivity parameters when the values of NSE, PBIAS and R2 are satisfactory. This instruction is practically suitable for our case (Table 4), indicating that the process of calibration of flows and sediments is within an acceptable range compared to the measured values. Regarding the validation of the model, it was carried out over eight-year from 1993 to 2000. Sufi-2 requires a single iteration with the the same number of simulation used for the calibration period [52]. It uses the same best ranges of sensitivity parameters obtained in calibration to reproduce the same simulation results in other periods [53]. The performance of the

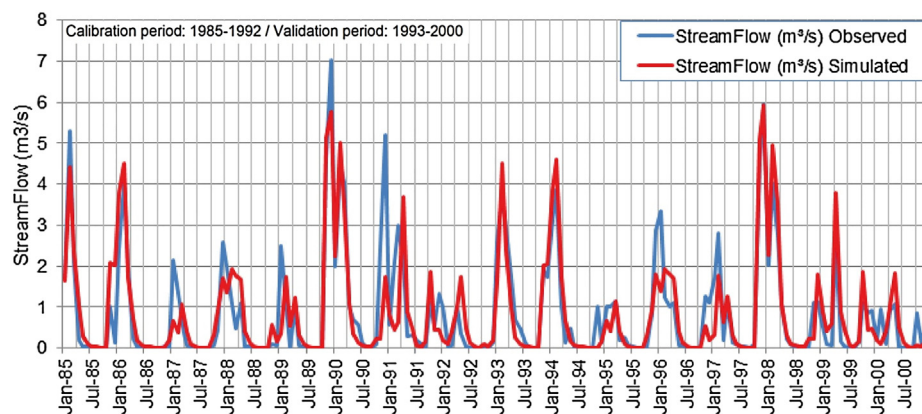


Fig. 6 Observed and simulated flows (StreamFlow) for the calibration and validation period (1985–2000).

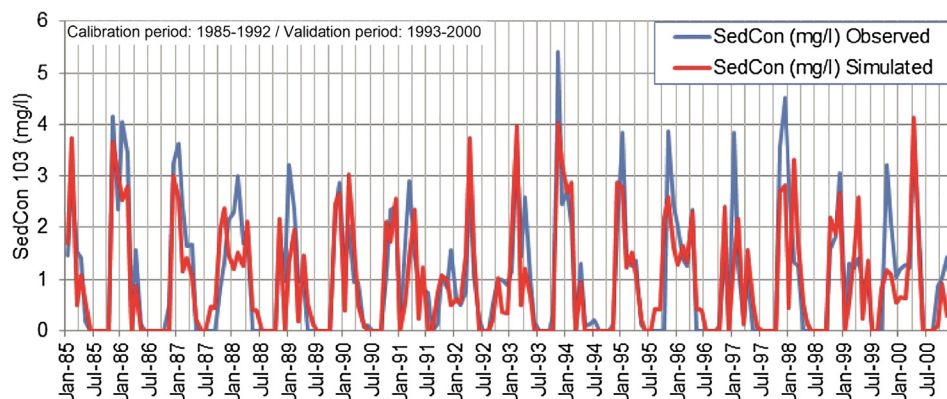


Fig. 7 Sediment concentrations (SedCon) observed and simulated for the calibration and validation period (1985–2000).

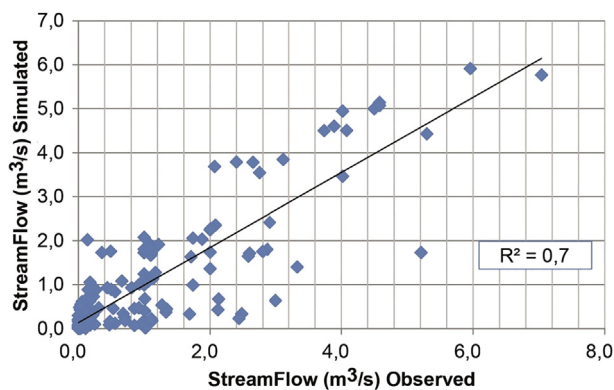


Fig. 8 Scatter plot of observed and simulated monthly flows (StreamFlow) for the calibration period (1985–1992).

validation period is also evaluated according to the output results of the objective functions used (NSE, PBIAS and R2), the values of these functions are acceptable and testify to a satisfactory validation of the model (Table 4) (see Figs. 10 and 11).

3.3. Water yield and water balance

The SWAT model estimates the values of the water balance and water yield components that are considered important

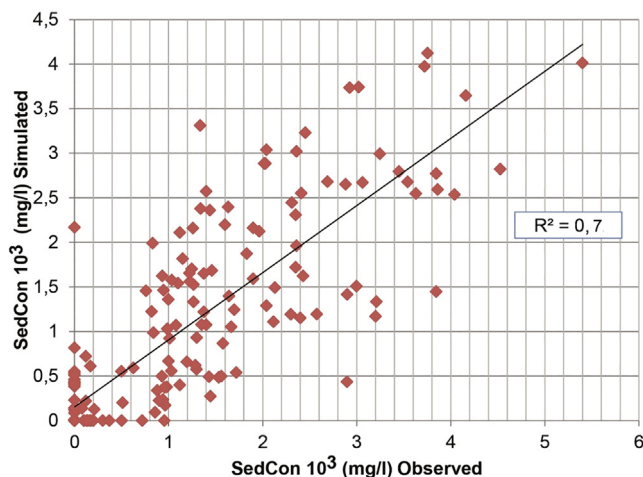


Fig. 9 Scatter plot of monthly sediments observed and simulated (SedCon) for the calibration period (1985–1992).

parameters for the management of water resources in a watershed [54]. To facilitate the analysis of water balance results, the simulation period was subdivided into four parts with a four-year interval (Fig. 12). This Figure shows that evapotranspiration is the parameter that contributes to the greatest water loss in the basin followed by surface flow. Evapotranspiration rep-

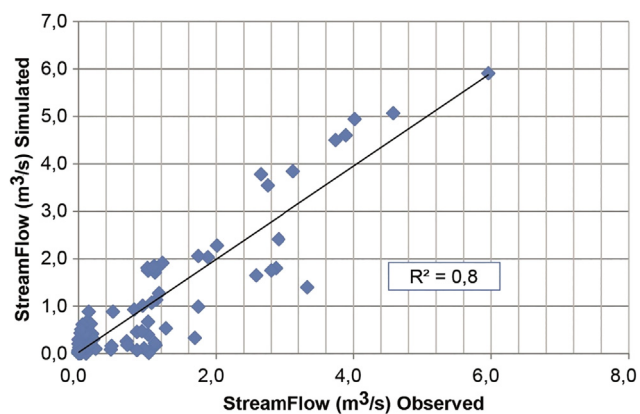


Fig. 10 Scatter plot of observed and simulated monthly flows (StreamFlow) for the validation period (1993–2000).

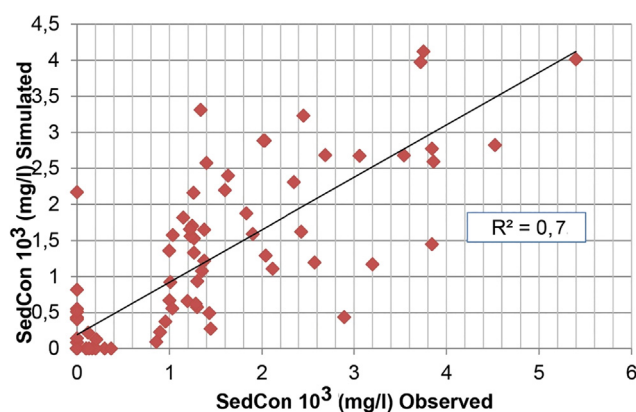


Fig. 11 Scatter plot of monthly sediments observed and simulated (SedCon) for the validation period (1993–2000).

represents 58.7% during the first period and then begins to decrease slightly towards the year 1996 where it represents 42.4%, concerning the SURQ, it represents 22.2% in the period of 1985–1988 and then increases over time to reach 32.9% in the year 1996. For the rest of the water balance component, it does not show much variation along the simulated period. Thus it can be said that only evapotranspiration and surface runoff dominate in the Arbaa Ayacha watershed. This is mainly due to the type of vegetation that prevails in the study area and sometimes to the rise in temperatures especially in the dry seasons. The annual averages of the different water balance components in each subwatershed as well as the annual average for the whole basin between 1985 and 2000 are shown in Fig. 13. Evapotranspiration and surface runoff represent 79.91% relative to the other water balance components, while the percentage of lateral flow and deep aquifer recharge is low and does not exceed 3.25%.

Regarding the distribution of the water balance components in each subwatershed, it is controlled by the type of land use, soil type, slope and quantity of precipitation. The maximum value of ET is recorded in sub-b21 while the minimum value is observed at sub-b27 and they are located in the south-west of the basin. SURQ is maximum in the center of the basin in sub-b20 and reaches 286.96 mm while its minimum value equals 140.20 mm located upstream in sub-b22. For GW_Q, it reaches its highest value at sub-b27 and the lowest value (69.08 mm) at the center of the basin especially in sub-b14. With regard to lateral flow (LATQ), it is too high upstream of the study area in sub-b24 reaching 35.80 mm and too low downstream of the basin at sub-b5 with a value equal to 3.22 mm. Concerning to water yield, the values predicted by the SWAT model, vary from 335.32 mm up to 407.76 mm with an average equal to 360.77 mm (Fig. 14). The maximum value of water yield is recorded at the sub-b26 and the minimum value in the sub-b25. The center of

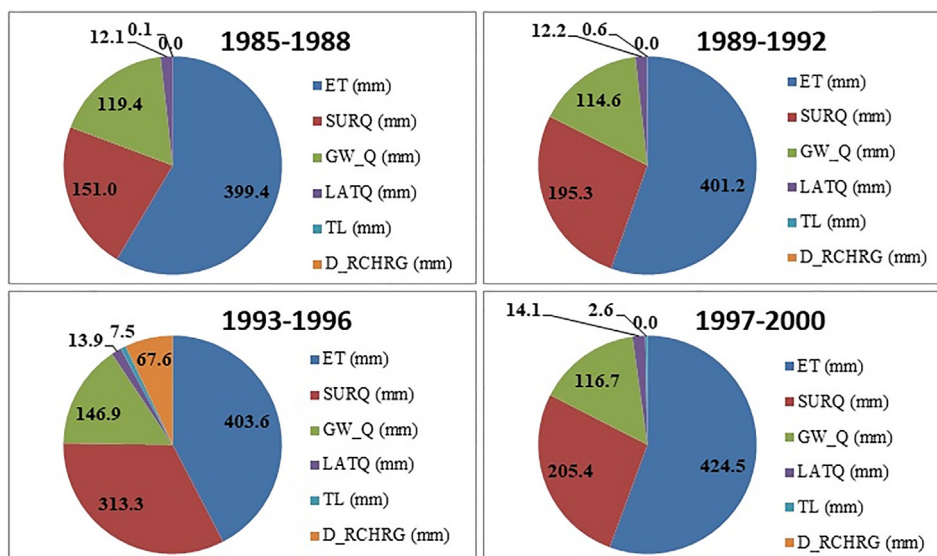


Fig. 12 Water balance for four different periods in the study area expressed in mm (ET: Evapotranspiration, SURQ: Surface runoff, GW_Q: Groundwater delay, LATQ: Lateral flow, TL: Transmission losses).

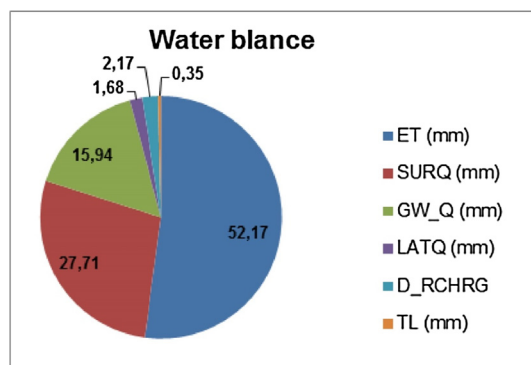


Fig. 13 Water balance for the simulated period (1985–2000) expressed as a percentage compared to annual precipitation (ET: Evapotranspiration, SURQ: Surface runoff, GW_Q: Groundwater delay, LATQ: Lateral flow, TL: Transmission losses).

the watershed generally has moderate values between 320 mm and 340 mm, whereas the downstream basin reflects low values below 320 mm. While, the highest values are recorded in the extreme north-east and south-west of the study area.

3.4. Sediments yield

After the calibration and validation period of the models with the best sensitivity parameters, SWAT-CUP generates text files illustrating the values of the monthly sediment yields in each sub-watershed. The resulting sediment yield values vary between 5.10 t/ha/year in sub-basin 7 and 67.54 t/ha/year

reported in sub-basin 14, with an average equal to 28.09 t/ha/year (Fig. 15). This Figure makes it possible to highlight the most productive zones of the sediments according to the erosion control factors. Indeed, the center of the basin is more productive of sediments, this zone is mainly occupied by friable Eocene marly formations, by high slopes, poorly developed soils, cropland and degraded matorral. These characteristics generate strong erosion by amplifying runoff and reducing infiltration. Downstream of the basin releases less sediment (sub-basins: 1,3,4,5,7,12), it constitutes a deposit area where materials from the slopes accumulate.

4. Discussion

The sensitivity analysis of the SWAT model in this study demonstrated that the parameters CN2, GW_DELAY and ALPHA_BF are the most influencing at flow rates. Whereas, the sediment concentration is more sensitive to the parameters USLE_P, SPCON and USLE_K. Other Moroccan watersheds with characteristics similar to our study areas have shown the sensitivity of flows and sediments to the same parameters proven in the current study. As an example, the Mikkes basin [55], the N'fis catchment [56], the Kalaya watershed [17] and the R'dom basin [57]. However, the present study added two parameters showing a degree of significant sensitivity. They are CH_COV1 and CH_COV2, which provide information on the erodibility of channels and their capacity for sediment transport. Regarding the performance of the model, the objective functions used have demonstrated a significant and satisfactory adjustment. However, model performance is not only controlled by the sensitivity parameters and objective func-

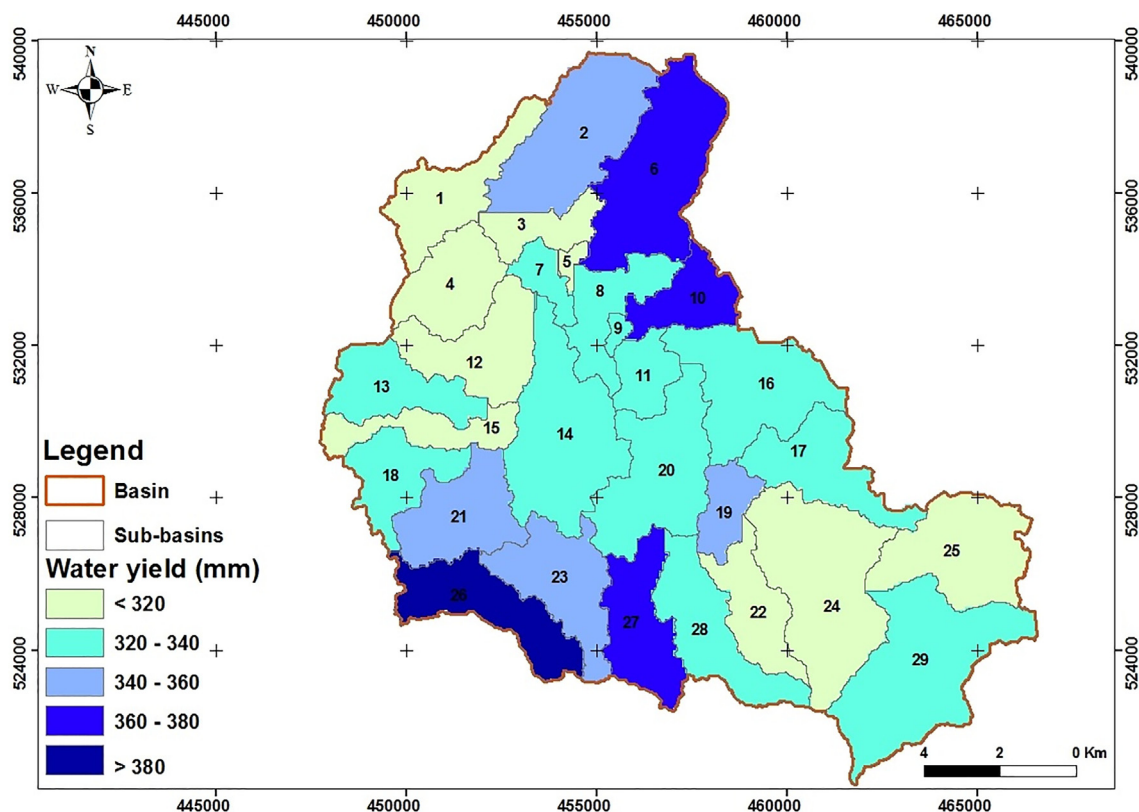


Fig. 14 Water yield distribution map in each sub-watershed of the study area.

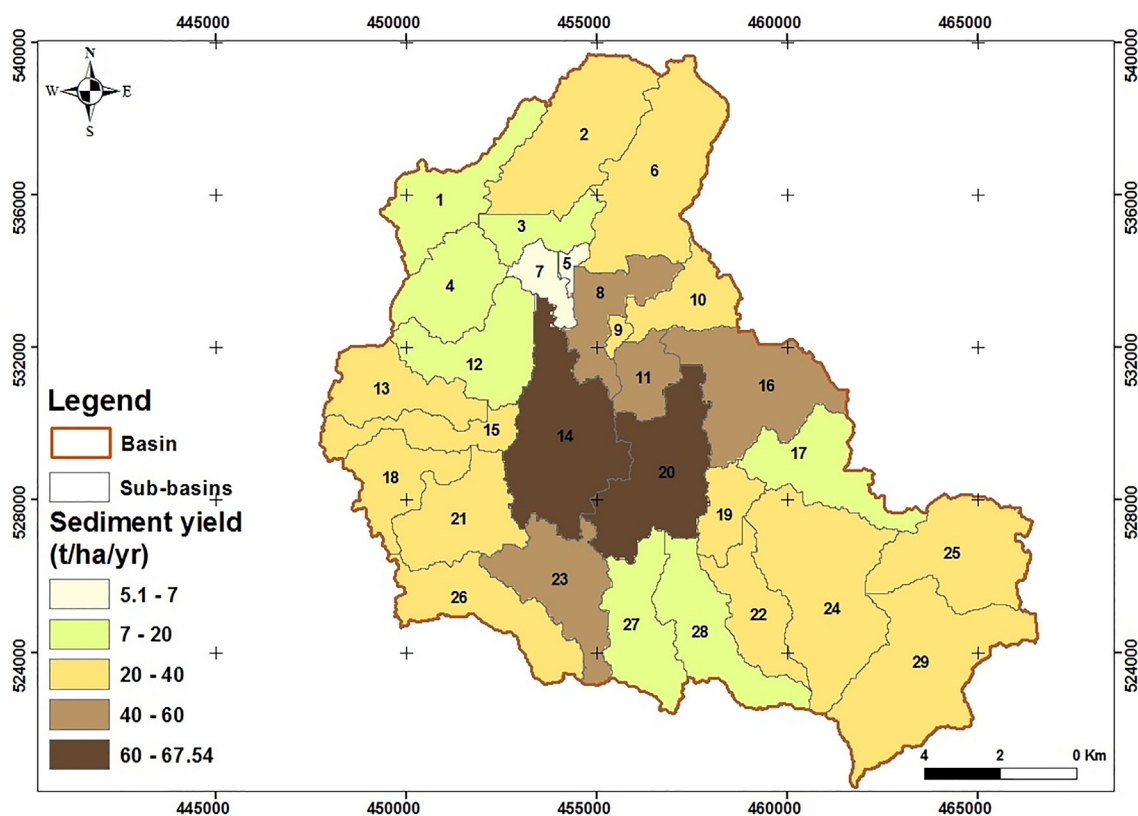


Fig. 15 Distribution map of sediment yield values in the watershed.

tions. It is also influenced by the reliability of the measured data (flow and sediment) in the hydrometric stations [58], and by the geographic location of these stations [59]. In our case, the five meteorological stations surrounding the basin are not sufficient to have more precision on the geographical distribution of rain. The hydrometric station allowing measurements of sediment flows and concentrations were installed in the center of the basin. This location is spatially inappropriate to have maximum influence on the performance of the model in the whole basin. In fact, a few peak flows and peak sediments were recorded in some months despite the absence of observed data and the absence of rain events. The same remark was made in the Tafna watershed in Algeria where SWAT can't detect small peaks [60]. Regarding the water balance, evapotranspiration is the most dominant component in the study area. This is related to the presence of bare land and agricultural areas. The firsts promote evaporation and the seconds increase transpiration. Surface runoff occupies second place in the watershed, the generation of this flow is mainly related to the physicochemical characteristics of the basin. These characteristics also control the distribution of the different components of water balance [61]. The marly and argillaceous nature of the substrate is the most dominant in the basin [7], these lithological formations favor surface runoff and limit water infiltration especially when combined with the effect of slopes and land cover. Similarly, water entering the soil to reach the aquifer may not be considered in its entirety, since it can participate in other flows outside the watershed [62]. Climate change can also influence the distribution of water balance, especially that the Moroccan Rif was

considered as an environment of significant climate change [63,64]. This change is manifested in our study by a remarkable rise in surface flows and water infiltration aquifer recharge with a slight decrease in evapotranspiration especially during the third period (1993–1996). Regarding the sediment yield values, the SWAT model has calculated an average annual equal to 28.09 t/ha/year, the maximum and minimum values are respectively 67.54 t/ha/year and 5.10 t/ha/year. These values are consistent with the average rates calculated in other surrounding watersheds [55–66] and prove the reliability of the model applied. Excessive sediment losses coincide with the Eocene marly formations in the center of the basin. This result is perfectly compatible with the application of the RUSLE model in the same basin, where the average erosion rates reach 25.05 t/ha/y [7], with high losses are located in the center of the basin. This zone is characterised by high slopes and bare lands which can release more sediment [18].

5. Conclusion

This work describes the results of flow and sediment dynamics simulated by the hydrological model SWAT in the Arbaa Aya-cha watershed. This model has been calibrated and validated on the watershed using a multi-objective optimization approach. The performance of the model was tested using three objective functions: NSE, PBIAS and R2 which gave acceptable and satisfactory results. The most adjusted sensitivity parameters for the study area correspond respectively to CN2, ALPHA_BF, GW_DELAY, GWQMN and CH_N2

for flow rates and to USLE_P, CH_COV1, USLE_K, SPCON and CH_COV2 for sediments. Concerning the evaluation of water erosion, the hydrological model gave average values of sediments yield of the order of 28.09 t/ha/year while the minimum and maximum losses are successively equal to 5.1 t/ha/year and 67.65 t/ha/yr with excessive losses are usually located in the center of the watershed. In terms of water balance, SWAT calculated its components in monthly average values over the simulated period. The water yield values range from 335.32 mm up to 407.76 mm with a mean equal to 360.77 mm. Evapotranspiration is prominent in the basin followed by surface runoff, while other water balance components are restricted in the area. The main causes are due to the type of land use, the variability of the rains and especially to the lithological nature of the substrates limiting the infiltration and amplifying the runoff. In general, the results obtained by the SWAT model in the area are encouraging, they can be exploited for the determination of best management practices for the basin. This model has correctly described the sedimentary and aquatic dynamics in the basin, therefore it can be used for the assessment of water balance and sediment dynamics in sub-humid watersheds of the western Rif of Morocco.

Declaration of Competing Interest

No potential conflict of interest was reported by the authors.

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